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Runoff, sediment, nitrogen, and phosphorus losses from agricultural land converted to sweetgum and switchgrass bioenergy feedstock production in north Alabama

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Abstract

Renewable energy sources such as bioenergy crops have significant potential as alternatives to fossil fuels. Potential environmental problems arising from soil sediment and nutrient losses in runoff water from bioenergy crops need to be evaluated in order to determine the sustainability and overall feasibility of implementing bioenergy development strategies. This paper discusses runoff, sediment, N, and total P losses from agricultural land (continuous cotton (*Gossypium hirsutum* L.)) converted to short-rotation sweetgum (*Liquidamber styraciflua* L.) plantations with and without fescue (*Festuca elatior* L.) and switchgrass (*Panicum virgatum* L.) bioenergy crops, compared to corn (*Zea mays* L.), on a Decatur silt loam soil in north Alabama, from 1995 to 1999. Runoff volume was significantly correlated to total rainfall and sediment yield in each year, but treatment differences were not significant. Sweetgum plots produced the highest mean sediment yield of up to 800 kg ha^{-1}compared to corn and switchgrass plots, which averaged less than 200 kg ha^{-1}. Runoff NH_4^+ N losses averaged over treatments and years for spring season (3.1 kg ha^{-1}) were three to five times those for summer, fall, and winter seasons. Runoff NO_3^- N for no-till corn and switchgrass plots in spring and summer were five to ten times that for sweetgum plots. No-till corn and switchgrass treatments had 2.4 and 2.1 kg ha^{-1} average runoff total P, respectively, which were two to three times that for sweetgum treatments. Growing sweetgum with a fescue cover crop provides significantly lower risk of water pollution from sediment, runoff NH_4^+ N, and NO_3^- N.

Keywords: Corn; Cover crops; Fertilizer; No-till; Soil erosion

1. Introduction

Conversion of agricultural land to bioenergy feedstock production presents great potential for pollution of surface and groundwater resources with fertilizer derivatives such as nitrate and phosphates, pesticides, and residual chemicals from herbicides [1]. Given the extensive land requirement necessary for production of large quantities of biomass crops for fuel, as well as their potential use for making fiber, it is important to assess environmental impacts of agronomic practices that could be used in the production of biomass crops. This information will be important in the development of sustainable and environmentally sound management strategies for bionergy feedstock production.

Nitrogen (NH_4^+ N and NO_3^- N), phosphorus ($H_2PO_4^-$ and HPO_4^{2-}), pesticide, and herbicide residues are major non-point sources of surface water pollution from agricultural production. Agriculture is a key source of NO_3^- N pollution in groundwater [2,3]. The major adverse health hazard caused by high NO_3^- N in water is methemoglobinemia in bottle-fed infants [4]. Nitrate concentrations in excess of 10 mg L^{-1} are considered unsafe for drinking water [2]. Loading of streams and rivers with surface

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runoff, eroded sediment, and groundwater discharge from agricultural land leads to pollution of surface and groundwater resources. In Alabama, non-point pollution of water resources has been attributed to agricultural activities [5].

High concentrations of P in surface waters, largely resulting from surface runoff of sediment P, causes eutrophication [6,7], which has been suggested as the main cause of impaired surface water resources [8]. Significant leaching of NO_3 to groundwater from corn plots receiving poultry litter has been reported [9]. To date, information documenting the long-term environmental impacts of conversion of agricultural lands for the production of bienergy crops is lacking. Some researchers predicted that conversion from agricultural crops to short rotation woody crops (SRWC) would result in reductions in soil erosion and chemical losses in runoff and groundwater [10,11]. These predictions indicated that most erosion losses with growing SRWC would occur in the first 2 years and decline with establishment of crops after the first 2 years.

Preliminary results from a study conducted on a loess soil in Mississippi [12] showed that sediment yield from tree crops was significantly lower than conventional tilled cotton and no-till corn, and nutrient losses of N and P in runoff water were primarily influenced by mineral fertilizer application in the spring. Conventional tillage systems for cotton normally include shredding of cotton stalks, tillage with moldboard or chisel plough, disking and/or harrowing for herbicide and fertilizer incorporation and seedbed preparation, and use of a field cultivator weed control. Typically, 12–15 tillage operations are performed prior to cotton harvest [13].

This paper summarizes the effects of a short-rotation sweetgum (*Liquidambar styraciflua* L.) plantation with and without a fescue (*Festuca elatior* L. var. Kentucky 31) cover crop and switchgrass (*Panicum virgatum* L. var. Alamo) bioenergy crops on runoff, sediment, N, and P losses, compared to no-till corn, var. Pioneer 3163, on a Decatur silt loam soil in north Alabama from 1995 to 1999.

2. Materials and methods

2.1. Study site

This study was conducted jointly by the Tennessee Valley Authority (TVA), Muscle Shoals, AL, the US Department of Energy's Bioenergy Feedstock Development Program (BFDP), Oak Ridge, TN, and Alabama A&M University, at the Winfred Thomas Agricultural Research Station, at Hazel Green, AL (latitude 34°54′ N and longitude 86°32′W), in the Limestone Valley region of north Alabama from 1995 to 1999. The soil is a Decatur silt loam (clayey, kaolinitic thermic, Rhodic Paleudults), which has been under conventional tillage cotton cultivation for at least 15 years. The site is characterized with a 4% slope, good natural drainage, intermediate erosion potential, and long-term (year average) annual rainfall of 1452 mm [14].

2.2. Plot layout and treatments

Eight pentagon-shaped runoff plots, four 0.2 ha and four 0.5 ha (Fig. 1), were established at the study site. An earth berm 0.5 m high was constructed around each plot to "hydrologically" isolate the plots from surrounding fields. The berms were seeded with fescue to minimize erosion. H-flumes 0.5 m wide were installed at the downslope point of the pentagon-shaped plots to collect runoff water. Four treatments of no-till corn, switchgrass, sweetgum, and sweetgum with fescue cover crop were randomly assigned to the plots with each treatment being assigned to one 0.5 ha plot and one 0.2 ha plot.

2.3. Management practices

Crop management practices used in the establishment and production of the row crops were chosen to represent recommended management practices by extension personnel in the area (Table 1). Sweetgum was planted at 1.5 m × 3.0 m spacing. Fescue was no-till drilled as a 2.0 m central strip between the sweetgum rows in spring 1995 on the sweetgum with cover crop treatment. Corn was no-till planted in spring each year as shown in Table 1. Switchgrass was already established in the plots and was not replanted.

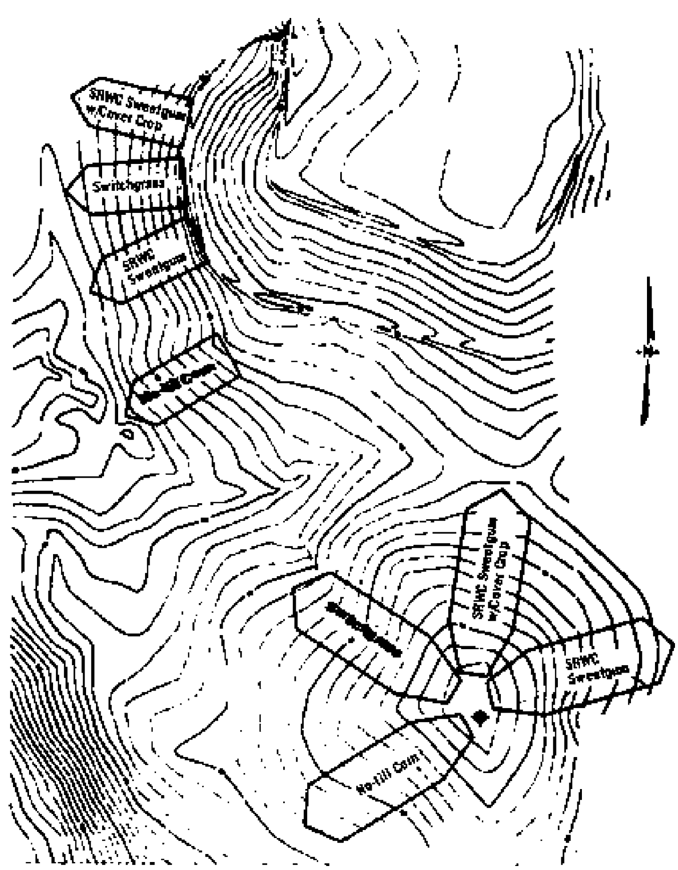

Fig. 1. Layout for no-till corn, switchgrass, sweetgum, and sweetgum with fescue cover crop treatments at Hazel Green, Alabama, 1995–1999.

Table 1
Crop management practices used in the establishment and production of corn, switchgrass, sweetgum, and sweetgum with fescue cover crop treatments, Hazel Green, AL, 1995–1998

Crop	Planting date	N and P fertilizer rates (kg ha^{-1}) and date of application (in parenthesis)	Herbicide and date of application	Harvest date
1995				
Sweetgum	02/15	None	Glyphosate as needed	None
Corn	04/12	134N, 67P (4/12)	Alachor, atrazine (4/07)	10/23
Switchgrass	05/23	67N, 67P (4/13)	None	10/19
1996				
Sweetgum	N/A	84N, 112P (4/24)	Glyphosate as needed	None
Corn	04/17	134N, 67P (4/17)	Alachor, atrazine (4/03)	8/30
Switchgrass	N/A	67N, 112P; 67N (7/09)	None	6/27; 10/09
1997				
Sweetgum	N/A	84N, 100P (4/09)	Glyphosate as needed	None
Corn	04/19	112N, 100P (4/09)	Alachor, atrazine (4/06)	10/01
Switchgrass	N/A	84N, 100P (4/09); 67N (7/22)	None	6/27; 10/09
1998				
Sweetgum	N/A	None	Glyphosate as needed	None
Corn	4/27	112N, 100P (4/28)	Alachor, atrazine (4/28)	10/15
Switchgrass	N/A	84N, 100P (4/28); 67N (7/23)	None	7/08; 10/26

Table 2
Analysis of variance showing effects of no-till corn, switchgrass, sweetgum, and sweetgum with fescue cover crop treatments on runoff, sediment yield, runoff NH_4^+ N, NO_3^- N, and P concentrations, Hazel Green, AL, 1995 to 1999

Source of variation	Runoff volume (m^3 ha^{-1})	Sediment yield (kg ha^{-1})	NH_4^+ N (kg ha^{-1})	NO_3^- N (kg ha^{-1})	P (kg ha^{-1})
	$\Pr > F$ value				
Year	0.8793 NS	0.0003 ***	0.5075 NS	0.0062 **	0.0004 ***
Season	0.9299 NS	0.0012 **	0.0080 **	0.0025 **	0.0105 **
Treatment	0.9705 NS	0.0001 ***	0.0757 NS	0.0003 ***	0.0001 ***
Year × season	0.9441 NS	0.0180 **	0.5965 NS	0.0008 ***	0.0003 ***
Year × treatment	0.9948 NS	0.0001 ***	0.7092 NS	0.0027 **	0.2910 NS
Season × treatment	0.9993 NS	0.1979 NS	0.3123 NS	0.0397 *	0.1909 NS
Year × season × treatment	0.9985 NS	0.0001 ***	0.8926 NS	0.1448 NS	0.9498 NS

*, **, ***, Significant at the 0.05, 0.01, 0.001 probability levels, respectively; NS, not significant.

2.4. Data collection and laboratory analyses

Runoff volume at each flume was continuously monitored and water samples proportional to the flow were collected throughout storm events. Runoff samples were, with few exceptions, collected within less than 12 h after the end of a precipitation event. A portion of each sample was filtered using a 0.45 μm pore diameter Millipore filter to remove suspended particles while the other portion was left unfiltered. Samples were stored at 4 °C and later analyzed for sediment and nutrient content. Sediment loss from plots was estimated by quantitatively weighing the sediment collected within each runoff sample after oven-drying at 105 °C for 24 h and converting to a kg ha^{-1} basis. The samples were analyzed for nitrate (NO_3^-), ammonium (NH_4^+), and total P (Kjeldahl digestion using acid ammonium persulfate and perchloric acid). A Lachat auto-analyzer (Lachat, Inc., Milwaukee, WI) was used for the analysis of nitrate and ammonium.

2.5. Statistical analysis

The data were statistically analyzed using the SAS general linear models procedure using SAS version 8e software. Mean separation was done using the least significant difference (LSD) test. Correlation analysis procedure was used to determine relations between the dependent variables and rainfall. Statistical significance was evaluated at the 0.05 probability level, unless given otherwise. A partial analysis of variance (ANOVA) table showing effects of year, season, treatments, and their

interaction on runoff, sediment yield, runoff NH_4^+ N, NO_3^- N, and total P concentrations is presented in Table 2.

3. Results and discussion

3.1. Surface runoff volume

Although there was more surface runoff from the sweetgum without cover, no-till corn, and switchgrass plots in the first growing season (spring 1995), the differences among years, seasons, and treatments during the study period were not significant (Table 2). Several factors such as surface soil physical properties, root channels, soil cracks, and micro-fauna activity influence soil infiltration rate, hence surface runoff. In addition, soil texture plays the most dominant role. Clayey-textured soils are more prone to high surface runoff [15], which results from a high proportion of micro-pores and surface sealing, thus masking treatment effects. Similar results showing no significant differences in runoff among tillage treatments have been reported in small watersheds in the Limestone Valley of north Alabama [16].

As expected, runoff volume was significantly correlated to rainfall volume and sediment yield in each year (Table 3). The direct relationship between rainfall and runoff has been found by other researchers [17]. Surface runoff can remove large quantities of both dissolved and sediment-bound nutrients from the soil [18], which will, over-time, significantly influence soil and water quality. At our study site, soil type, which was the same for all the treatments, had more influence on the amount of surface runoff volume thereby masking treatment effect on runoff volume.

3.2. Sediment yield

Soil sediment loss from agricultural land is of critical importance because it not only signifies loss of a valuable resource—soil, but highlights additional environmental implications such as water pollution by fertilizer nutrients and harmful chemical residues. Sediment yield refers to the amount of soil particles leaving a location and is a cumulative result of soil detachment by erosion, deposition, and transportation by flowing water. Seasonal trends in sediment yield and rainfall from 1995 to 1999 for no-till corn, switchgrass, sweetgum, and sweetgum with fescue cover crop treatments are presented in Fig. 2. There was a significant ($P<0.001$) year $\times$ season $\times$ treatment interaction for sediment yield (Table 2). Although no significant treatment differences in surface runoff were observed, significant differences in sediment yield were detected. These data are similar to those from other studies which reported that surface residues may reduce soil erosion more than they reduce surface runoff [19].

Sediment yield from plots under traditionally tilled sweetgum trees was significantly greater than from plots under no-till corn, switchgrass, and sweetgum with a fescue cover crop, in 1995, 1996, and 1997 (Fig. 2). This can be explained by the fact that the canopy of sweetgum trees was not as effective in protecting the soil from the direct impact of raindrops as that of corn, fescue, and switchgrass due to lack of adequate soil cover. The grass treatments

Table 3
Correlations between total rainfall, runoff, sediment yield, runoff NH_4^+ N, NO_3^- N, and P concentrations, Hazel Green, AL, 1995 to 1999

	Rainfall (mm)	Sediment yield, ($kg\,ha^{-1}$)	NH_4^+ N ($kg\,ha^{-1}$)	NO_3^- N ($kg\,ha^{-1}$)	P ($kg\,ha^{-1}$)
	1995				
Runoff ($m^3\,ha^{-1}$)	0.64 ***	0.35 ***	0.01 NS	−0.10 NS	−0.14 NS
Rainfall (mm)		0.02 NS	−0.22 *	−0.27 **	−0.20 *
Sediment yield ($kg\,ha^{-1}$)			0.54 ***	0.44 ***	0.26 **
1996					
Runoff ($m^3\,ha^{-1}$)	0.62 ***	0.28 **	−0.12 NS	−0.16 NS	−0.28 **
Rainfall (mm)		0.08 NS	−0.16 NS	−0.21 *	−0.27 **
Sediment yield ($kg\,ha^{-1}$)			0.04 NS	0.02 NS	0.25 **
1997					
Runoff ($m^3\,ha^{-1}$)	0.55 ***	0.33 *	−0.23 NS	−0.24 NS	−0.31 *
Rainfall (mm)		0.20 NS	−0.24 NS	−0.54 ***	−0.44 **
Sediment yield ($kg\,ha^{-1}$)			−0.21 NS	0.10 NS	−0.13 NS
1998					
Runoff ($m^3\,ha^{-1}$)	0.38 **	0.40 **	−0.08 NS	−0.06 NS	−0.21
Rainfall (mm)		0.11 NS	−0.12 NS	−0.13 NS	−0.21 NS
Sediment yield ($kg\,ha^{-1}$)			0.01 NS	0.01 NS	−0.09 NS
1999					
Runoff ($m^3\,ha^{-1}$)	0.44*	0.61 **	−0.39 *	−0.29 NS	−0.52 NS
Rainfall (mm)		0.37 NS	−0.35 NS	−0.25 NS	−0.65 *
Sediment yield ($kg\,ha^{-1}$)			−0.24 NS	0.28 NS	−0.36 NS

*, **, ***, Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; NS, not significant.

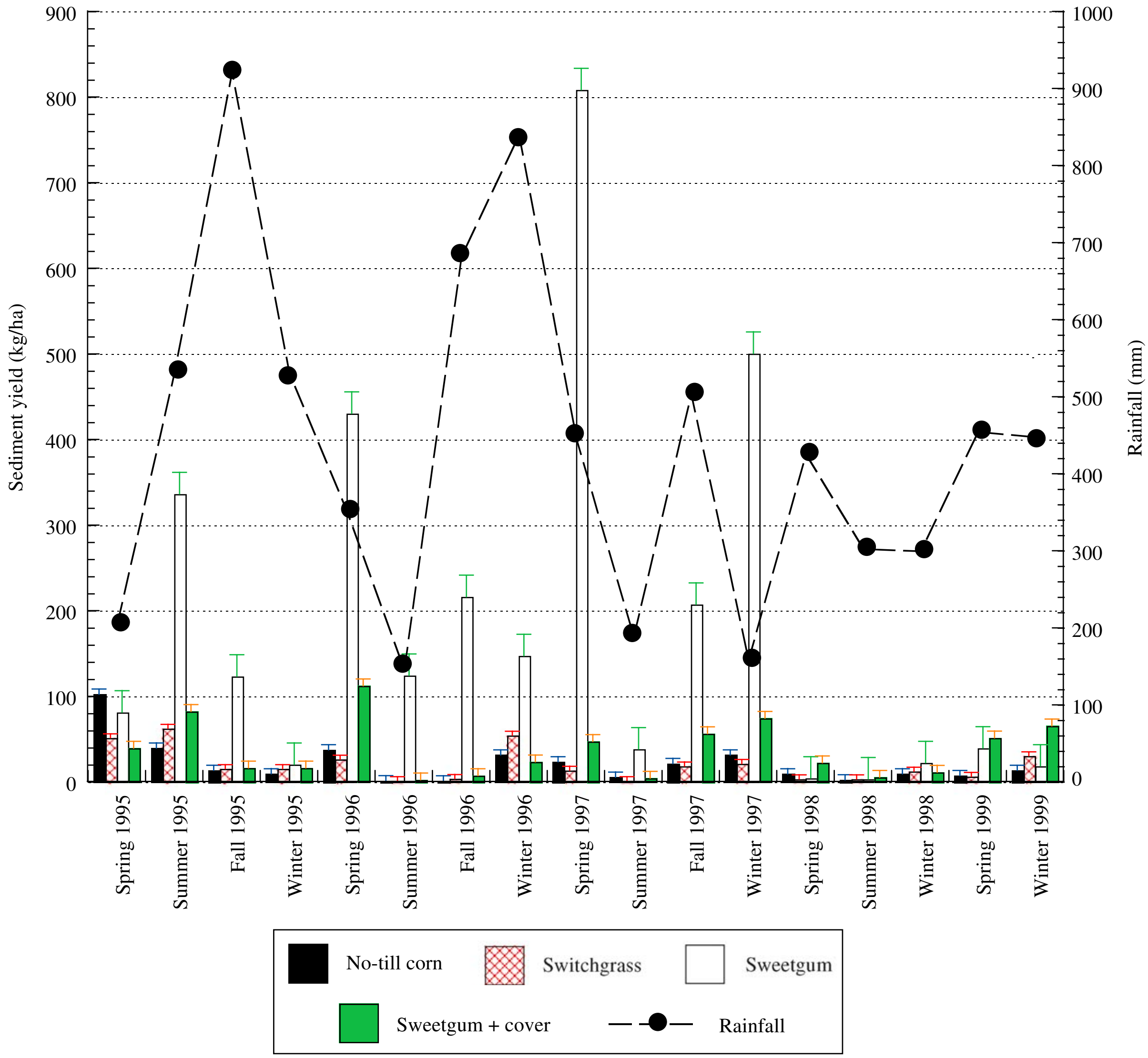

Fig. 2. Sediment yield from plots under no-till corn, switchgrass, sweetgum, and sweetgum + cover crops in spring, summer, fall, and winter seasons, Hazel Green, AL, 1995–1999 (error bars = S.E. of means).

(sweetgum with cover and switchgrass) produce more surface reside cover faster than the tree species. Energy from the direct impact of raindrops on the soil surface is a major factor causing the breakup of soil particles generating sediment [20]. Therefore, plants which develop a good canopy cover early after establishment play a significant role in reducing soil erosion. In addition, the shallow and fibrous root systems of corn, switchgrass, and fescue (grass plants) give additional protection against sediment loss and soil erosion by holding soil particles together compared to the deep tap root system of sweetgum. Furthermore, raindrops falling from the canopies of the taller sweetgum trees, particularly during leafless periods during early establishment and growth, carry more erosive force compared to those falling from the short dense canopies such as that of corn, switchgrass, and fescue [21].

Planting a fescue cover crop between sweetgum rows (sweetgum + fescue cover crop treatment) resulted in a significant reduction in sediment yield compared to the sweetgum without cover (sweetgum treatment) during 1995, 1996, and 1997 (Fig. 2). This further supports the efficiency of the grass plants in reducing soil erosion and sediment due to their growth characteristics and fibrous root system. However, in 1998 and 1999, there was no significant difference in sediment yield from sweetgum without cover crop and sweetgum with cover crop treatments. This was attributed to 3 years of sweetgum leaf litter mulch accumulation which provided complete cover on the soil surface thus protecting the soil from erosion. Therefore, no additional benefit of a cover crop between the sweetgum rows in terms of reduction in sediment yield by 1998 and 1999.

Mean sediment yields from plots under sweetgum with fescue cover crop, no-till corn, and switchgrass were under $100\,kg\,ha^{-1}$ in each year and season, whereas that from plots under sweetgum trees without fescue cover crop

ranged from 100 to 800 kg ha^{-1} (Fig. 2). Sediment yield was significantly correlated ($P<$ 0.001) to runoff but not to total rainfall (Table 3). Fig. 2 shows that sediment yield in seasons with highest total seasonal rainfall was not necessarily higher than that from seasons with lower total rainfall. These results suggest that some, but not all, rainfall events resulted in significant sediment yield. It takes rainfall events with intensities of up to 15 mm h^{-1} sustained for an extended period to significantly affect the rainfall erosivity factor, hence to affect soil erosion [21]. This makes rainfall intensity, rather than total rainfall, more important in affecting sediment yields.

There was a general decline in sediment yield from plots under no-till corn from 100 kg ha^{-1} in spring 1995 to less than 10 kg ha^{-1} in 1998 and 1999. The highest sediment yield for the no-till corn treatment was in spring 1995; this was following land-use conversion from traditional tillage to no-till. Carryover of previous years' corn crop residues can result in cumulative buildup of protective surface soil residue cover. Research elsewhere [22] showed that surface crop residues increased with time under no-tillage with corn due to residue carryover from year to year. Crop residues increase soil surface roughness which reduces raindrop impact, erosivity, surface runoff of water, and promotes infiltration.

3.3. Runoff NH_4^+ N

NH_4^+ N is easily transported in runoff water due to its high water solubility and its association with negatively charged soil colloids eroded by runoff. There were no significant differences in runoff NH_4^+ N loss due to treatments (Table 2). However, runoff NH_4^+ N loss averaged over treatments and years for spring season, which was 3.1 kg ha^{-1}, was 2.5 times that for summer season which was 1.2 kg ha^{-1}, 4.5 times that for fall season which was 0.7 kg ha^{-1}, and eight times that for winter season which was 0.4 kg ha^{-1} (Fig. 3). The significantly high runoff NH_4^+ N loss in spring compared to the other seasons can be explained by the fact that N fertilizer applications were done in spring. Therefore, the risk of the available NH_4^+ N being lost in surface runoff was significantly higher for this time period. Plant uptake, nitrification, and other factors reduce the amount of available NH_4^+ N, resulting in significantly lower values of runoff NH_4^+ N later in the season each year. To reduce runoff NH_4^+ N loss in spring, split application of N is recommended.

There was no significant correlation between NH_4^+ N loss and total runoff suggesting that the total amount of runoff water was not the critical factor in the transport of NH_4^+ N from the source plots under study. A significant correlation ($r = 0.54$) between sediment yield and NH_4^+ N content in 1995 indicated that NH_4^+ N bound to sediment particles contributed more to NH_4^+ N in runoff water early in the study (Table 3). However, in 1996, 1997, and 1999, there were no significant correlations between sediment yield and NH_4^+ N content. Runoff of NH_4^+ N into fresh water resources is one of the factors which promotes eutrophication, a condition of undesirable and excessive plant growth. In water, the process of nitrification converts NH_4^+ N to NO_3^- N, which can cause more serious health hazards to humans. Therefore, runoff NH_4^+ N from bionergy crops in spring need to be addressed to reduce the potential for NO_3^- N pollution of water.

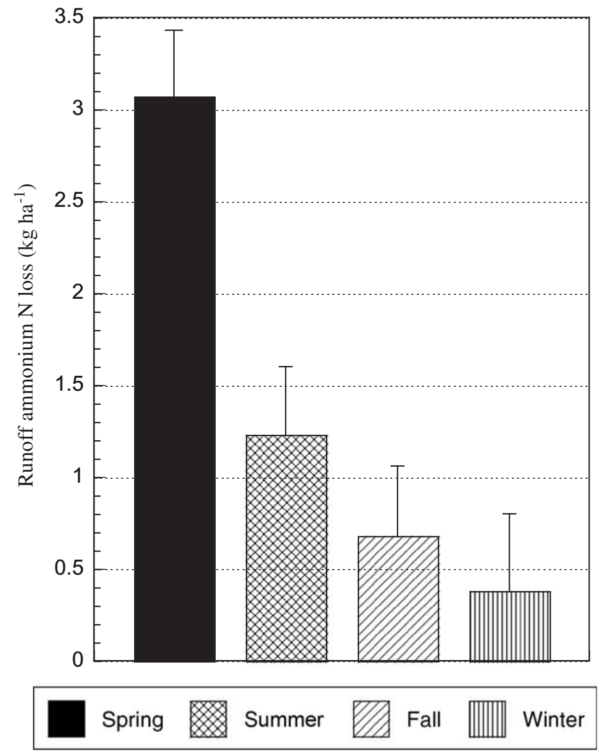

Fig. 3. Runoff ammonium N loss (kg ha^{-1}) from plots under no-till corn, sweetgum with and without cover crop, and switchgrass, in spring, summer, fall, and winter seasons, Hazel Green, AL, 1995 to 2000 (error bars = S.E. of means).

3.4. Runoff NO_3^- N

There were significant year × season, year × treatment, and season × treatment interactions for runoff NO_3^- N loss (Table 2). Data showing these interactions are presented in Fig. 4. In 1995, runoff NO_3^- N loss in spring was 10.5 kg ha^{-1} which was 3, 26, and 35 times as much as that in summer (3.8 kg ha^{-1}), fall (0.4 kg ha^{-1}), and winter (0.3 kg ha^{-1}), respectively (Fig. 4). In the same year, runoff NO_3^- N loss in summer was significantly greater than that in fall and winter. Results for 1996 and 1997 show no significant difference in runoff NO_3^- N loss between seasons, although figures for summer were generally higher. No data were collected in the fall of 1998 and 1999 and in summer of 1999 due to field recording equipment breakdown; hence, the results were not conclusive. However, runoff NO_3^- N loss for spring and summer were greater than those for winter in 1998 while in

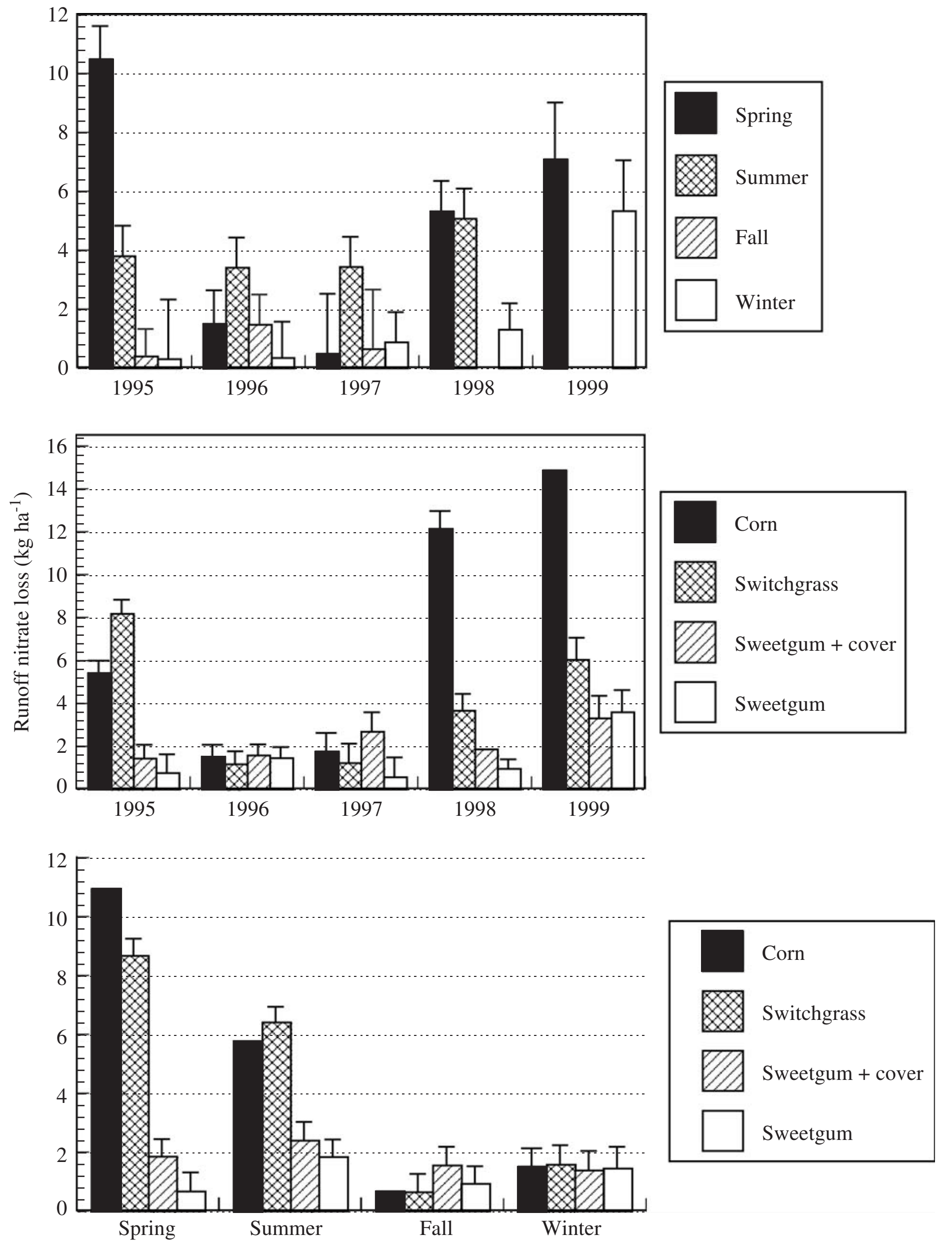

Fig. 4. Runoff nitrate losses (kg ha^{-1}) from plots under no-till corn, sweetgum with cover crop, sweetgum without cover crop, and switchgrass, in spring, summer, fall, and winter seasons, Hazel Green, AL, 1995–1999 (error bars = S.E. of means).

1999, runoff NO_3^- N loss for spring was significantly greater than that for winter season.

As was observed with runoff NH_4^+ N loss, the consistently higher runoff NO_3^- N loss values during the spring correspond with the timing of N fertilizer application. In addition, removal of NO_3^- N from the soil profile by plant uptake and leaching reduces the amount available for loss in surface runoff; thus, there is a progressive decline in runoff NO_3^- N loss with time during the growing season. Table 3 shows that runoff NO_3^- N loss during the first 3 years of study (1995, 1996, and 1997) was negatively correlated with total rainfall. Seasonal rainfall distribution (Fig. 2) shows that in each year, spring and summer seasons generally had the least total rainfall figures, despite having higher values of runoff NO_3^- N loss. These results indicate that time of application, and not total rainfall, was more important in influencing runoff NO_3^- N loss from the plots. Similarly to runoff NH_4^+ N, split application of N fertilizer would be recommended to reduce loss of NO_3^- N in surface runoff in the spring.

Runoff NO_3^- N loss from plots under no-till corn and switchgrass were significantly higher than that from plots under sweetgum and sweetgum with fescue cover crop in 1995, 1998, and 1999 but not in 1996 and 1997 (Fig. 4). Corn and switchgrass plots received N fertilizer every year, whereas those with sweetgum only received N fertilizer in 1996 and 1997 (Table 1). Runoff NO_3^- N loss from corn plots was about 5, 12, and 15 kg ha^{-1}, respectively, in 1995,

1998, and 1999. Similar figures for runoff NO_3^- N loss from switchgrass plots were about 8, 4, and 6 kg ha^{-1}, respectively. The above figures range from two to four times those from plots under sweetgum or sweetgum with fescue cover crop. Therefore, crops requiring yearly application of N fertilizer to achieve optimum growth pose a higher risk of contributing to water pollution from runoff NO_3^- N.

The interaction between season and treatment on runoff NO_3^- N loss is illustrated in the bottom graph in Fig. 4. Averaged over treatments and years, runoff NO_3^- N loss for no-till corn and switchgrass plots in spring and summer were five to ten times that for sweetgum and sweetgum with fescue cover crop. This can be explained by the fact that corn and switchgrass plots received N fertilizer every year and that the fertilizer was applied during spring. On the other hand, plots for sweetgum and sweetgum with fescue cover crop only received N fertilizer in 1996 and 1997. As explained earlier, the amount of NO_3^- N available for loss in surface runoff in any given year decreased with time during the growing season, and therefore, fall and winter seasons had significantly lower values of runoff NO_3^- N loss. The above results show that time and frequency of N application were critical in causing NO_3^- N loss from agricultural land converted to bioenergy feedstock production. Our study shows that conversion of agricultural land to a bioenergy plantation may have significant effects on the amount of NO_3^- N ending up in groundwater unless a cover crop is included to reduce runoff especially in the first 2 years of establishment.

3.5. *Runoff P*

Unlike N which is usually present in sufficient quantities, P is the limiting nutrient for primary plant growth in water bodies. Runoff P from the field plots was significantly affected by the treatments and also by year × season interaction (Table 2). No-till corn and switchgrass treatments had 2.4 and 2.1 kg ha^{-1} runoff P, respectively, which were two to three times that for sweetgum and sweetgum with fescue cover crop (Fig. 5). Runoff P was negatively correlated to rainfall in 4 out of 5 years and positively correlated to sediment yield in 1995 and 1996 (Table 3). The results for runoff P are consistent with data for sediment yield, which indicated that seasons with highest total rainfall did not necessarily result in higher runoff P compared to those with lower total rainfall.

The effect of year × season interaction on runoff P is shown in Fig. 6. In spring 1995 and 1998, runoff P for spring was higher than that for the other seasons, whereas in 1996 and 1997, spring had the lowest runoff P. In years in which sweetgum plots received P fertilizer (1996 and 1997), runoff P for summer and fall seasons were highest (Fig. 6). After application to the soil, P is quickly fixed through a series of precipitation and adsorption processes of phosphate ions with organic matter or metals such as aluminum and iron [23]. As the year progresses, the sites available for P fixation and adsorption decline or become saturated, hence more P is available for runoff.

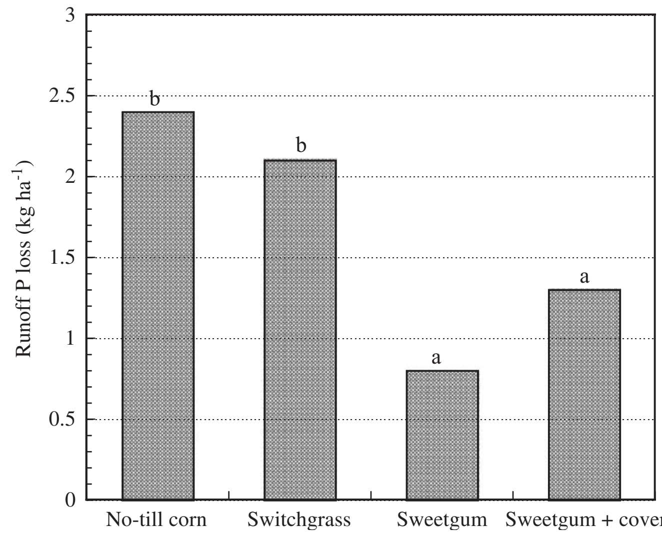

Fig. 5. Runoff P losses (kg ha^{-1}) from plots under no-till corn, switchgrass, sweetgum, and sweetgum with cover crop treatments, Hazel Green, AL, 1995–1999 (letters show mean separation by LSD procedure at 5% level).

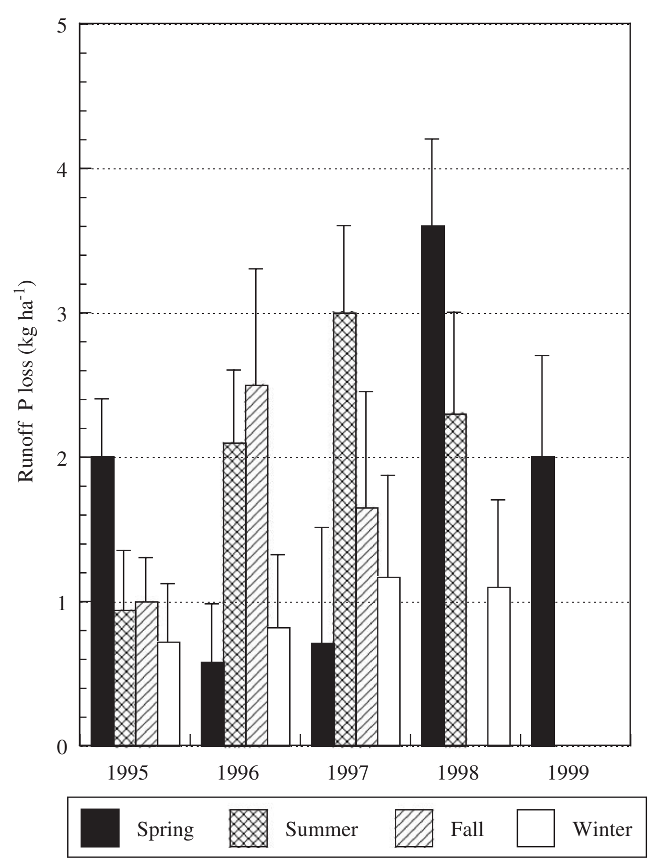

Fig. 6. Runoff P losses (kg ha^{-1}) in spring, summer, fall, and winter seasons, Hazel Green, AL, 1995–1999 (error bars show S.E. of means).

Phosphorus concentrations of up to 0.025 mg L^{-1} are capable of causing eutrophication in surface waters [1].

Severe problems of eutrophication of rivers and lakes have been attributed to P losses from agricultural areas [24]. Our study shows that conversion of cropland to a sweetgum plantation results in less runoff P which may end up in surface waters compared to row crops such as corn. This is mainly due to the fact that sweetgum does not require as much P fertilizer application as corn or switchgrass. Since leaching is considered to be of little significance in P contributions which can result in eutrophication [25], reducing P fertilizer application to agricultural land will reduce the amount of P in surface runoff and soil sediment, thereby slowing down or preventing the process of eutrophication of surface waters. Matching P application rates with no-till corn and switchgrass use requirements can provide an effective mechanism to ensure that these crops can provide environmentally sustainable resources for bioenergy and agriculture.

4. Conclusions

This study shows that sweetgum with a fescue cover crop during the first 2 years has a significantly lower risk of causing water pollution from sediment, runoff NH_4^+ N, and NO_3^- N compared to row crops such as corn even when corn is grown no-till. Surface runoff volume was not significantly affected by the no-till corn, switchgrass, sweetgum, and sweetgum with fescue cover crop treatments. Sediment loss from sweetgum plots was generally higher during the first 3 years following planting but thereafter, sediment yields were generally low in all treatments. Planting a fescue cover crop between the sweetgum rows significantly reduced sediment loss during the first 3 years after planting. Runoff NH_4^+ N was significantly higher in spring of each year and was not significantly affected by treatments. However, runoff NO_3^- N from plots under no-till corn and switchgrass was significantly higher than that from plots under sweetgum and sweetgum with fescue cover crop in 3 out of 5 years when the trees were not fertilized. In addition, runoff NO_3^- N for no-till corn and switchgrass plots in spring and summer was five to ten times that for sweetgum and sweetgum with fescue cover crop. Runoff P from no-till corn and switchgrass treatments was two to three times as much as that for sweetgum and sweetgum with fescue cover crop. Timing application of fertilizer and matching nutrient requirements of switchgrass and no-till corn can enhance the viability of this energy crop and agriculture crop and minimize their role as sources of NO_3^- N and P.

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References

[1] Daniel TC, Sharpley AN, Lemunyon JL. Agricultural phosphorus and eutrophication: a symposium overview. Journal of Environment Quality 1998;27:251–7.
[2] Spalding RF, Exner ME. Occurrence of nitrate in groundwater—A review. Journal Environment Quality 1993;22:392–402.
[3] Lichtenberg E, Shapiro LK. Agriculture and nitrate concentrations in Maryland community water system wells. Journal Environment Quality 1997;26:145–53.
[4] National Research Council. Nitrate and nitrite in drinking water. Washington, DC: National Academic Press; 1985.
[5] Alabama Cooperative Extension System. Water quality: Nonpoint Source (NPS) pollution of Alabama waters. Circular ANR-790-4.1, 1995.
[6] Schindler DW. Evolution of phosphorus limitation in lakes. Science 1977;195:260–2.
[7] Sharpley AN. Availability of residual phosphorus in manured soils. Soil Science Society America, Journal 1996;60: 1459–66.
[8] USEPA. Environmental indicators of water quality in the United States. EPA 841-R-96-002, 1996.
[9] Liebhardt WC, Golt C, Tupin J. Nitrate and ammonium concentrations of ground water resulting from poultry manure applications. Journal of Environment Quality 1979;8,211–5.
[10] Hohenstein WG, Wright LL. Biomass energy production in the United States: an overview. Biomass and Bioenergy 1994; 6:161–73.
[11] Ranney JW, Mann LK. Environmental considerations in energy crop production. Biomass and Bioenergy 1994;6:211–28.
[12] Thornton FC, Joslin JD, Bock BR, Houston A, Green TH, Schoenholtz S, et al. Environmental effects of growing woody crops on agricultural land: first year effects on erosion and water quality. Biomass and Bioenergy 1998;15:57–69.
[13] Keeling W, Segarra E, Abernathy JR. Evaluation of conservation tillage cropping systems for cotton on the Texas Southern High Plains. Journal of Production Agriculture 1989;5:269–73.
[14] Green TH, Brown GF, Bingham L, Mays D, Sistani K, Joslin JD, et al. Environmental impacts of conversion of cropland to biomass production. Proceedings of bionergy '96—the seventh national bioenergy conference: partnerships to develop and apply biomass technologies, 1996. p. 918–24.
[15] Rosenthal WD, Hipp BW. Field and model estimates of pesticide runoff from turfgrass. In: Racke KD, Leslie AR, editors. Pesticides in urban environments—fate and significance. Series 522. Washington, DC: American Chemical Society; 1993. p. 208–13.
[16] Soileau JM, Touchton JT, Hajek BF, Koo KH. Sediment, nitrogen, and phosphorus runoff with conventional tillage cotton in a small watershed. Journal of Soil and Water Conservation 1994;49:82–9.
[17] Brakensiek DL, Rawls WJ. An infiltration based rainfall runoff model for SCS Type 2 distribution. Transactions of the American Society of Agricultural Engineers 1982;25:1607–11.
[18] Lawrance R, Williams R. Carbon movement in runoff and erosion under simulated rainfall conditions. Soil Science Society America, Journal 1998;52:1445–8.
[19] Unger PW, Langdale GW, Papendick RI. Role of crop residues—improving water conservation and use. In: Hargrove WL, editors. Cropping strategies for efficient use of water and nitrogen. ASA Special Publication No.51, 1998. p. 69–100.

[20] Al-Durrah MM, Bradford JM. The mechanism of raindrop splash on soil surfaces. Soil Science Society America, Journal 1982;46:1086–90.

[21] Foster GR, Young RA, Romkens MJM, Onstad CA. Processes of soil erosion by water. In: Follett RF, Stewart BA, editors. Soil erosion and crop productivity. 1985: p 137–62.

[22] Halvorson AD, Peterson GA, Reule CA. Tillage system and crop rotation effects on dryland crop yields and soil carbon in the Central Great Plains. Agronomy Journal 2002;94:1429–36.

[23] Nair VD, Graetz DA, Reddy KR. Dairy manure influences on phosphorus retention capacity of spodols. Journal of Environment Quality 1998;27:522–7.

[24] Sharpley AN, Halvorson AD. The management of soil phosphorus availability and its impact on surface water quality. In: Lal R, Stewart BA, editors. Soil processes and water quality. Boca Raton: FL: Lewis Publ.; 1994. p. 7–90.

[25] Sharpley AN, Menzel RG. The impact of soil and fertilizer phosphorus on the environment. Advances in Agronomy 1987;41:297–324.